The Earth's Worst Climate Disaster
By Robert Kopp and Joseph Kirschvink

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Scientists, environmentalists, and the wiser members of the political class worry today about global climate change. Will rising tides plunge Tokyo, London, and New York beneath the ocean's waves? Will meltwater pouring off of North America shift the circulation of the North Atlantic Ocean and plunge Europe into an Ice Age? Yet, as worrisome as these prospects are, the Earth has faced far greater climatic catastrophes in the past. The greatest among these was the Paleoproterozoic Snowball Earth event, which 2.3 billion years ago smothered the planet with a blanket of ice for tens of millions of years.

At the beginning of the Paleoproterozoic Era, 2.5 billion years ago, the Earth was a far different place than it is today. The cores of the ancient continents – the Canadian Shield of North America, the Pilsbara Craton of Australia, the Kalahari Craton of southern Africa – had just begun to form.

Though the Sun was only four-fifths of its present brightness, the planet was warmer; some studies of the oxygen isotopes of ancient chert and phosphate minerals suggest that it may have been 60ºC warmer – too hot for plant or animal life. Only once does the rock record an interval before 2.5 billion years ago when, as today, there were glaciers on the Earth.

Climate modelers believe the explanation of this apparent paradox rests in the composition of the atmosphere. In today's atmosphere, the concentration of methane, a potent greenhouse gas, is about 2 parts per million. It is kept low because 20% of our atmosphere is oxygen. Once sparked by light or heat, methane and oxygen react rapidly together to produce carbon dioxide and water – a reaction utilized by those who heat their homes with natural gas.

Two and a half billion years ago, however, most researchers think the atmosphere was essentially free of oxygen. Methane concentrations could build up to levels a thousand times higher than at present. High levels of methane, combined with high levels of carbon dioxide, kept the planet toasty.

Life was only single-celled. Because most single-celled organisms make poor fossils, we do not know how closely the ancient bacteria resembled their modern descendants. Roger Summons from MIT and Jochen Brocks from Harvard have found in 2.7 billion year old Australian rocks organic molecules, hopanes and steranes, that look like they may have been produced by cyanobacteria and eukaryotes.

Cyanobacteria, once known as blue-green algae, are bacteria that act like plants -- they use energy from light to transform water into oxygen; indeed, they are relatives of the chloroplasts that perform the reaction in plants. Today, they are the main producers of certain types of molecules called hopanols. The eukaryotes, the domain of life that includes plants, animals, and yeast, produce sterols in a process that now require oxygen. Cyanobacterial hopanols and eukaryotic sterols transform into hopanes and steranes over geologic time. Yet we do not know for certain that cyanobacteria and eukaryotes, as opposed to now-extinct ancestors or cousins, were responsible for the ancient organic molecules.

Shortly after 2.5 billion years ago, the global climate began to change. Glaciers began to advance and retreat. The first three glaciations of this time period are recorded in rocks from the Huronian Supergroup of central Canada. Glaciers grind up rocks into powder as they scrape across the land surface,.When they reach the oceans they break off into icebergs that slowly melt and drop powder and stones onto the ocean floor. The jumbled remains of the collapse – pebbles, cobbles, and boulders, called clasts, embedded in fine-grained material called the matrix – form a type of sedimentary rock called a diamictite. Glaciers are not the only agents that can form diamictites, but glacial transport leaves distinctive signatures, including scratches in multiple directions caused as rocks carried in a glacier scrap across the country rock. Three major Huronian diamictites tell geologists that the Earth in Huronian times had cooled considerably. Huronian time was a glacial age, with temperatures as cold as those today, if not colder.

Taking Ancient Latitudes

One major open question about the Huronian glaciations is how close to the equator that occurred. In the recent ice ages, glaciers in North America extended to around 40ºN latitude, somewhat farther than Chicago. As Eiichi Tajika discussed earlier, climate modelers such as Ken Calderia of Lawrence Livermore National Laboratory and Jim Kasting of Pennsylvania State University have shown that, if glaciers penetrated below about 30° in latitude, they would trigger an "ice-albedo runaway". Because ice reflects most of the Sun's light, extending the glaciers would cool the planet further until all the continents, and perhaps all the oceans as well, became encased in ice, in what is called a "Snowball Earth" event.

In order to determine whether the Huronian diamictites record Snowball Earth events or more ordinary ice ages, scientists need a way of determining the latitude at which they formed. If the diamictites were shown to have formed at low latitudes, they would suggest a Snowball Earth event had occurred. Paleomagnetism, the study of magnetic signatures left in ancient rocks, provides the key to addressing the question.

The Earth is a giant magnet. Liquid iron circulating in the Earth's core produces the planet's magnetic field. The field, which on average through time aligns with the axis about which the Earth spins, protects the planet from solar radiation and allows people to navigate using a simple magnetic compass. At the magnetic equator, the field is parallel to the surface of the Earth; at the poles, it is vertical, which is why compasses are not very useful in the Arctic.

Certain minerals are magnetic. Magnetite, known to the ancients as lodestone, is the best-known example. When these minerals form or are deposited in sediments, their own magnetic fields align with that of the Earth. If they formed at the equator, their fields will be horizontal; at the poles, they will be vertical. Using sensitive magnetometers, paleomagnetists can detect the magnetic fields preserved by these minerals in rocks and determine the latitude at which a rock formed.

Unfortunately, magnetic orientations are not forever. If a rock is heated to too high a temperature, or subjected to too high a pressure, its magnetic field will be reset and will be oriented with the field it experienced at the time of alteration. When the geology of a site is favorable, paleomagnetists can conduct tests to determine whether alteration has occurred.

One such test, the fold test, can be applied to sedimentary rocks that have been folded. Folding can occur either before sediments harden into rock or later, when they are subjected to pressure from other rocks. In a folded rock that preserves its original magnetic orientation, the measured orientations will vary across the fold. When the rock is mathematically unfolded, the directions will converge. On the other hand, if the magnetic orientations were reset after folding, the measured orientations will not vary across the fold and will diverge when the rock is unfolded.

Unfortunately, many old rocks have been beaten up rather badly by geological processes. They sometimes get cooked and altered to the point where their original magnetic minerals loose all memory of their original magnetism. This seems to be the case for the Huronian rocks in Canada. On a field trip to Canada in 2002 with colleagues from the University of Tokyo, we found a well-preserved fold in an outcrop of hematite-rich sediments that formed just after one of the major glaciations. Magnetic patterns from the fold demonstrated conclusively that none of the original magnetic directions had been preserved. There is therefore no evidence that the glaciations preserved in Canada were low-latitude, Snowball Earth events;, they could instead be mid-latitude glaciations like those that have occurred in the last ten million years. Several geologists have also noted that these rocks do not have the pattern of post-snowball limestones that would form from the large concentration of atmospheric CO_2 built up during the glaciation.The precise age of the Huronian glaciations is not known, but a minimum age is. An igneous intrusion, the Nipissing diabase, penetrates the Huronian rocks and is therefore younger than them. By measuring the concentrations of different isotopes of lead produced by the decay of uranium, several groups of researchers have dated the Nipissing diabase to 2.22-2.21 billion years ago. Because we know this date, we can look elsewhere on the planet for rocks of the same age.

The least altered rocks from this time are located in southern Africa. Remarkably, the Ongeluk basalt, a lava flow in the Transvaal Supergroup there, bears the same 2.22 billion year age as the Nipissing diabase. The Ongeluk lava occurs mixed with a diamictite formation, the Makganyene diamictite. The diamictite includes multiply-striated clasts, the fingerprint indicating that it was produced by a glaciation.

As a graduate student at Caltech, David Evans, now a professor at Yale, studied the Ongeluk lava. He found that its magnetic orientation indicated that it formed only 11^{o} of latitude from the equator. Moreover, he conducted a breccia test, a test analogous to the fold test based on the measurement of the directions preserved in different clasts of a rock, and proved that the low latitude was, indeed, original. The Huronian glaciations may not have been Snowballs, but the magnetic data indicates the Makganyene glaciation was. It is also followed by some of the most unusual sediments on this planet.

Bacteria Throwing Snowballs

What caused the Earth to plunge into its coldest and longest ice age? The answer to that question depends upon whether the Makganyene Snowball was an isolated event, or whether the Huronian glaciations that preceded it were also Snowballs David Evans believes that the Huronian glaciations – indeed, every glaciation of the Precambrian epoch, which runs from the formation of the Earth to the time of the rise of animal life 540 million years ago – was a Snowball glaciation. He suggests that this change may be the result of long-term changes. Perhaps, by 540 million years ago, the Sun was warm enough to prevent Snowballs. Perhaps, as Paul Hoffman of Harvard University suggests, animals, by disturbing soil and sediments, decreased the effectiveness with which photosynthesizers could remove atmospheric carbon dioxide and bury it as organic matter.

In contrast to Evans, we think that the Makganyene glaciation may have been the only Snowball in the Paleoproterozoic. Diamictites formed during Snowball events are generally overlain with distinctive and unusual sediments – cap carbonates and banded iron formations. These are present after the Makganyene glaciation, but not after any of the Huronian glaciations. Thus, in the absence of paleolatitude data and the rocks indicative of a Snowball, we think the Huronian glaciations were mid-latitude glaciations like the glaciations of more recent times and that the Makganyene Snowball was a symptom of a major transformation brought about by life.

Cyanobacteria, the blue-green microbes that transform water into oxygen in the process of turning carbon dioxide into organic matter, are not the only bacteria that can perform photosynthesis. Other, more ancient bacteria, called purple and green bacteria because of their distinctive colors, can also transform carbon dioxide into organic matter, but they require certain ions – typically, iron or sulfide – to do so. Of all microbes, cyanobacteria alone can photosynthesize using only water.

The more ancient bacteria could therefore thrive only in regions rich in iron or sulfide. When cyanobacteria finally evolved, photosynthesis was unleashed upon the low-iron and low-sulfide portions of the world, limited only by the availability of nutrients like phosphate. Their greater range should have allowed the cyanobacteria to come to dominate life on Earth quickly and start releasing large amounts of oxygen.

Today, oxygen is both a dangerous toxin and an element essential for complex life. The damaging effects of oxygen are why anti-oxidants have become a dietary fad. But the Earth's atmosphere has contained significant amounts of oxygen for about half the planet's life, and we have all evolved mechanisms for coping with the damage oxygen causes. When cyanobacteria first appeared, no organisms could deal with oxygen poisoning. Cyanobacteria, of course, had to develop a mechanism for surviving oxygen before they could thrive; once they did so, their ability to poison other organisms would have strengthened their dominant position.

The oxygen would have destabilized the methane greenhouse that kept the planet warm. Based on simple models we have constructed, cyanobacteria might have been able to destroy the greenhouse in less than 100,000 years, although it might have taken millions of years under a more conservative set of assumptions. In either case, the results suggest that the cyanobacteria evolved later than Brocks and Summons' organic molecules suggest they did, and that, when they did evolve, the global consequences were severe. Without the methane greenhouse, average global temperatures would have plummeted to –50ºC. Ice would have sheathed the oceans and the continents.

Yet life managed to survive this disaster. Perhaps, in certain spots, the ocean's ice cover was thin enough that sunlight could still penetrate beneath. Photosynthetic microbes might then continue to eke out a minimal existence, as could the microbes that rely on photosynthesizers to produce organic carbon. At deep-sea vents, heat-loving bacteria would have continued on with their existence, unaffected by the cold happenings kilometers above them.

Too, we do not know how well life did survive the Snowball. Since most microbes leave at best crude fossils, scientists do not know what microbes were around 2.2 billion years ago. By comparing the genomes of extent organisms, molecular biologists can reconstruct ancestral trees and estimate when organisms evolved. But the method is limited: were our only record of the dinosaurs the genomes of birds, we would know nothing of the gigantic herbivore *Apatosaurus* or the fierce *Tyrannosaurus*. Likewise, the Paleoproterozoic Snowball may have driven many lineages of organisms extinct without leaving us any traces.

Aftermath

For a long time, climate researchers dismissed Snowball Earth scenarios as a flaw in their models. Once the Earth entered a Snowball, they did not see how it could get out. In 1992, however, one of us (Joe

Kirschvink) realized the answer. Throughout the Snowball period, volcanoes remained active. Volcanic gases, including carbon dioxide, built up in the atmosphere. Under normal conditions, carbon dioxide dissolves in the ocean and reacts with dissolved ions like calcium to form carbonate rocks. Carbon dioxide cannot, however, dissolve in an ice-covered ocean; it can only accumulate in the atmosphere. Eventually, enough carbon dioxide would build up to heat the planet and end the Snowball.

For tens of millions of years after the onset of the Paleoproterozoic Snowball Earth, the Earth remained a frozen planet. After a long time – perhaps thirty million years, perhaps seventy million years, a span longer than the time period that separates us from the dinosaurs – carbon dioxide became the most abundant gas in the atmosphere. As the bright ice melted, the darker oceans and continents were exposed and sped the planetary warming. By the time the last ice vanished from the Earth, average global temperatures may have exceeded 50ºC.

During the long glacial interval, carbon dioxide was not the only substance accumulating. Far beneath the oceans' icy tops, deep-sea vents released iron, manganese, and various trace metals and nutrients. Most forms of life need such trace metals to thrive. Since life, barely surviving during the Snowball, was not able to use all the metals being released, they built up and fertilized the oceans.

The melting of the ice fostered a global bloom. Cyanobacteria once again released oxygen into the environment, but since the Earth was no longer dependent on a methane greenhouse, it was safe from a second Snowball. The oxygen did, however, react with the iron and manganese dissolved into the oceans. The iron rusted and precipitated out in finely layered deposits called banded iron formations, which extended over hundreds of square kilometers. The manganese reacted with oxygen to form the world's largest manganese deposit, the Kalahari Manganese Field. In parts, the Kalahari Manganese Field, which dominates the world's manganese production, holds high-grade deposits of manganese ore nearly 80 meters thick.

The hot conditions of the post-glacial world fostered gigantic storms and rapid weathering of the continents. Ions like calcium were carried from rocks dissolved on to the continents into the oceans. These ions reacted with dissolved carbon dioxide, the concentration of which was driven to extreme levels by the thick atmosphere. The result was the rapid formation of carbonate rocks, first recognized as being linked to the Snowball aftermath by Paul Hoffman, called 'cap carbonates' because of their position above the Snowball diamictite. Carbonate formation decreased the amount of carbon dioxide in the atmosphere and brought milder global temperatures.

Life recovered from the Snowball catastrophe, but the Earth was permanently changed. The onset of the Snowball marked the beginning of the reign of cyanobacteria and the age of oxygen. Many of the microbes that dominated the pre-Snowball world survived, but their descendants were driven off the Earth's surface, into low-oxygen environments in the soil, the sediments, and low-oxygen water bodies like the Black Sea. Though disastrous, the rise of oxygen and the Paleoproterozoic Snowball allowed the development of more complex life forms, including – though they would not appear for more than a billion years – plants and animals. We owe our existence to the bacteria that may have caused the world's worst climate disaster.

For further reading

THE SNOWBALL EARTH. P. F. Hoffman and D. P. Schrag in *Scientific American*, v. 282, no. 1 (January), p.p. 68-75.

PALEOPROTEROZOIC SNOWBALL EARTH: EXTREME CLIMATIC AND GEOCHEMICAL GLOBAL CHANGE AND ITS BIOLOGICAL CONSEQUENCES. J. L. Kirschvink, E. J. Gaidos, L. E. Bertani, N. J. Beukes, J. Gutzmer, L. N. Maepa, and R. E. Steinberger in *Proceedings of the National Academy of the Sciences*, vol. 97, no. 4, p.p. 1400-1405.

SNOWBALL EARTH. G. Walker; Crown Press, New York, 288 pages, 2003.

Figures

Figure 1: Striations formed by a glacier in a cobble from the Makganyene diamictite, South Africa.

Figure 2: The folded rock from Canada that demonstrated that we do not know the latitude at which the Huronian glaciations occurred.

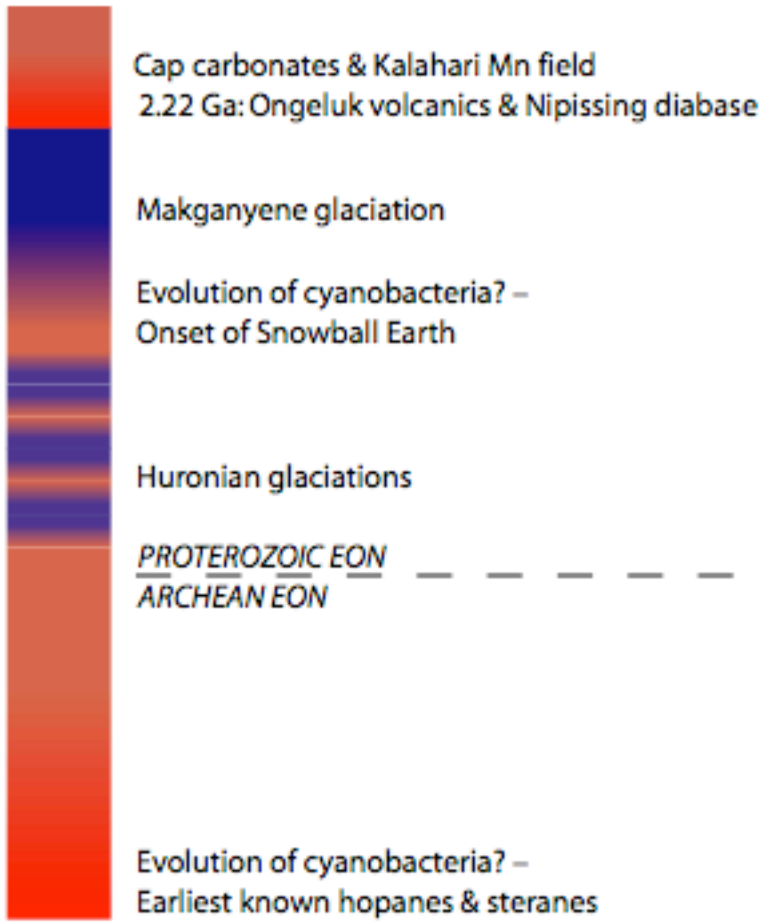

Figure 3: Timeline of events (Huronian and Makganyene)